A regional comparison of the effects of climate change on agricultural crops in Europe

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Abstract The effects of climate change will be felt by most farmers in Europe over the next decades. This study provides consistent results of the impact of climate change on arable agriculture in Europe by using high resolution climate data, socio-economic data, and impact assessment models, including farmer adaptation. All scenarios are consistent with the spatial distribution of effects, exacerbating regional disparities and current vulnerability to climate. Since the results assume no restrictions on the use of water for irrigation or on the application of agrochemicals, they may be considered optimistic from the production point of view and somewhat pessimistic from the environmental point of view. The results provide an estimate of the regional economic impact of climate change, as well as insights into the importance of mitigation and adaptation policies.

1 Introduction

Agriculture is the primary user of land, and water globally, and still defines society in many rural areas of Europe. European agriculture accounts for one half of the global trade of food products and is directly influenced by European and global policy (Smith 2009; FAOSTAT 2010). Climatic conditions directly affect agriculture and the water resources needed to maintain a stable production in many areas of Europe (Iglesias et al. 2007, 2009, 2011). It is likely that the stress imposed by climate change on agriculture and water will enhance existing regional disparities in rural areas of European countries and elsewhere (IPCC 2007; EEA 2008; Stern et al. 2006; Olesen and Bindi 2002; Carter 2010). Understanding the impact of climate change is inherently difficult because changes in physical and social variables are often based on different assumptions on inputs and are derived for geographical and time scales that often do not coincide. As a result, some of the most significant impacts of climate change may be more difficult to project than the future climate itself.

Ensuring an optimal level of adaptation in Europe requires consistent spatial information on impacts and regional disparities (COM 2009). Evidence suggests that information on likely future climatic and socio-economic conditions is crucial for developing mitigation and adaptation policies that are relevant at the European and local levels. Climate change will have a differential effect on regional agriculture due to a combination of contrasting baseline conditions and differences in the magnitude and rate of change. Despite these challenges, understanding the uncertainty associated with different assumptions may help guide the adaptation of agricultural policy to climate change in Europe.

Adaptation is a key factor that will shape the future severity of climate change impacts on food production (Iglesias et al. 2011; Lobell et al. 2008; Brooks et al. 2005; Burton and Lim 2005; Howden et al. 2007). Prioritizing climate change adaptation policies in the agricultural sector requires information on: (a) physical and economic impacts that refer to the same assumptions about social, economic and environmental scenarios; (b) spatial impacts to evaluate regional disparities and local realities; and (c) uncertainty. Here we follow a consistent methodology to evaluate these three aspects relevant to climate policy.

The remainder of this article is organized as follows: The second section provides information on the methodological approach while the third section describes the results of the physical impacts estimated at the European scale. Section 4 estimates the economic impacts using a general equilibrium approach and the final section presents the conclusions of the study.

2 Methods

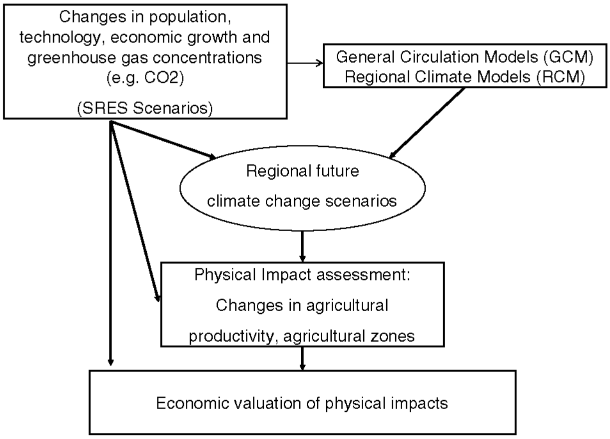
2.1 The modelling approach

We develop European scenarios of agricultural change for the 2080s based on global scenarios of changes in environmental and social variables and an understanding of the sensitivity of each agricultural region to these changes. We identify changes in agroclimatic regions. We estimate changes in crop productivity under climate change scenarios. For this purpose we develop statistical models of crop yield response based on process-based crop models, linking productivity, management and climate variables, as detailed below; livestock production is not considered. Finally, we use the changes in crop productivity to derive changes in economic variables by using a global equilibrium model. Figure 1 shows how scenarios interact with the physical and economic components of the study. The socio-economic scenarios are, at the same time, determinants of the possible adaptation options, since economic development is a driver of technological change, population defines demand and consumption, and land use change is influenced by policy.

2.2 Climate change scenarios

European climate change is characterised using dynamically downscaled climate model-based scenarios produced in the European PRUDENCE project (Christensen et al. 2007).

Fig. 1 Global and regional change scenarios and interactions with the physical and economic components of the study



Since no single projection is a prediction, scenarios represent alternative futures. Here we use four climate change scenarios, provided by the PRUDENCE project (Christensen et al. 2007). The scenarios are constructed from general circulation model (GCM) outputs (simulations with the HadCM3 and ECHAM4 models) driven by the A2 and B2 emissions scenarios defined in the IPCC Special Report on Emissions Scenarios (SRES – Nakicenovic et al. 2000) and downscaled for Europe with the HIRHAM and RCA3 regional climate models (RCM) (Table 1). The SRES represent potential socio-economic futures that in turn determine the level of greenhouse gas emissions to the atmosphere. Each socio-economic scenario takes a different direction of future developments. Here we consider the SRES A2 and B2, to be consistent with the approach applied in other sectoral and integrated analyses, which this study is a part of (Christensen et al. 2011).

2.3 Estimation of changes in agro-climatic regions

Monthly time series of average temperature and precipitation for 247 stations were provided by the National Oceanographic and Atmospheric Administration (NOAA) and were used to create a gridded database of temperature and precipitation period-mean values and yearly anomalies with a resolution of 50×50 km. The length of the time series at the stations is 30 years. Stations are identified in the gridded database by latitude, longitude, and altitude. This set of stations includes the nine sites with daily climate records used in the process-based crop model simulations (Parry et al. 2004; Iglesias et al. 2000). Crop production statistical data were available at NUTS 2 level from Eurostat and irrigation areas in a gridded database with a resolution of 50×50 km were obtained from FAO. Nine agro-climatic regions shown in Fig. 2 were defined using K-mean cluster hierarchical classification of the spatial climatic and crop data using the SPSS statistical program including the climate, crop and irrigation variables, following previous studies (Holden and Brereton 2004; Iglesias et al. 2000). The final regional classification was obtained after seven steps in this statistical procedure. Stations with altitudes higher than 1100 m and those that did not correlate with any of the nine sites with daily climate records were eliminated. Differences in seasonal temperature and the amount and distribution of precipitation, the type of crops and the irrigation practices result in the definition of nine regions. In northern regions, seasonal precipitation meets crop water demand during the entire crop cycle. Very low spring temperatures in the northern areas limit the crop growing season. The south-western regions are characterised by high spring and summer temper-

Table 1 Summary of the four climate scenarios used in the study (Source of data: Christensen et al. 2007; Average CO_2 concentration and population from Nakicenovic et al. 2000)

Definition of variables	Scenarios			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Complete name	HadCM3 A2/DMI/ HIRHAM 2080s	HadCM3 B2/DMI/ HIRHAM 2080s	ECHAM4/OPYC3 A2/SMHI/ RCA3 2080s	ECHAM4/OPYC3 B2/SMHI/RCA3 2080s
Short name	HadCM3 A2	HadCM3 B2	ECHAM A2	ECHAM B2
Time frame	2071–2100	2071–2100	2071–2100	2071–2100
Driving Socio-economic scenario	A2	B2	A2	B2
Driving Global circulation models (GCM)	HadCM3	HadCM3	ECHAM4	ECHAM4
Regional climate models (RCM)	DMI/HIRHAM	DMI/HIRHAM	SMHI/RCA3	SMHI/RCA3
Average CO_2 ppmv	709	561	709	561
Europe population change % (SRES, driver of GDP in the GTAP model)	8.9	−3.9	8.9	−3.9
Change in average annual temperature averaged over the European area considered in this study (deg C)	3.1	2.7	3.9	3.3

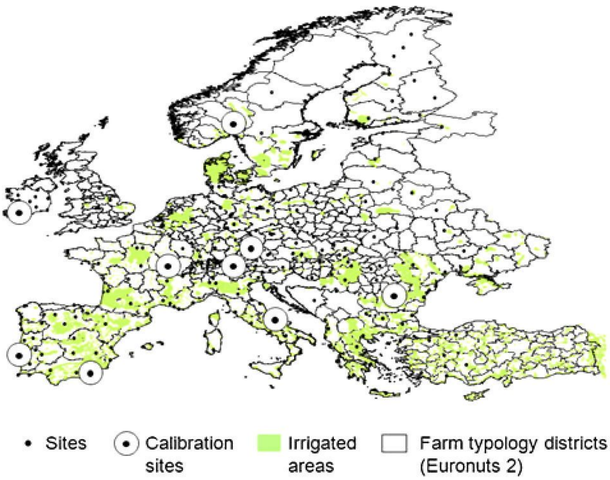


Fig. 2 Crop modelling sites (9 sites for process based models, large dots on the map; and 247 sites for statistical functions of yield response, small dots on the map), irrigated areas (shaded areas in the map) and farm typology districts (Euronuts 2 level, polygons in map)

atures, with a precipitation pattern that does not meet crop water requirements during the spring and summer and characterized by high climate variability. The continental regions are characterised by large seasonal temperature differences and low precipitation levels in the main agrarian counties. The typical Mediterranean region has small seasonal temperature differences and precipitation totals which decrease with latitude.

2.4 Estimation of changes in crop productivity

Process-based crop models provide the means to derive information of crop responses to climate and management when experimental data is not available (Lobell and Burke 2010; Iglesias et al. 2000; Porter and Semenov 2005; Steduto et al. 2009; Hansen and Jones 2000). Nevertheless, process-based crop models are data intensive, including daily climate data, soil characteristics and definition of crop management. Usually data constraints limit the use of models to sites where the information necessary for calibration is available. In this study, we select nine sites to represent the major agro-climatic regions in Europe derived earlier. At each site, process-based crop responses to climate and management are simulated by using the DSSAT crop models for wheat, maize, and soybeans (Jones et al. 2003; Rosenzweig and Iglesias 1998). Modelled wheat responses to climate are representative of possible responses of winter cereals in all regions and winter and spring cereals in the Mediterranean regions. The response of maize response represents most summer irrigated crop whereas soybean response to climate represents many leguminous crops in the different regions. The chosen crops are representative of approximately two thirds of arable land in most regions and have been used in numerous occasions to represent world food production (e.g. Parry et al. 2004; Lobell and Burke 2010; Hammer et al. 2005; Challinor et al. 2005).

DSSAT simulates daily phenological development and growth in response to environmental factors (soil and climate) and management (crop variety, planting conditions, nitrogen fertilisation, and irrigation). The DSSAT models can simulate the current understanding of the effect of CO_2 on crops (Long et al. 2006). Daily climate data for the 1961 to 1990 time period was obtained from NOAA; soil characteristics and management data were obtained from agricultural research stations. Crop distribution and production data were obtained from EUROSTAT.

For each of the nine sites, three crops and thirty years of daily climate, we conducted a sensitivity analysis to environmental variables (temperature, precipitation and CO_2 levels) and management variables (planting date, nitrogen and irrigation applications) (3600 simulations per site). The resulting output was then used to define statistical models of yield response for each site. This approach has proven useful for analysis in China (Rosenzweig et al. 1999), Spain (Iglesias et al. 2000; Iglesias and Quiroga 2007; Quiroga and Iglesias 2009), and globally (Lobell and Burke 2010; Lobell et al. 2008; Parry et al. 2004; Rosenzweig et al. 2004). Variables explaining a significant proportion of simulated yield variance are crop water (sum of precipitation and irrigation) and temperature over the growing season. The functional forms for each region represent the realistic water limited and potential conditions for the mix of crops, management alternatives, and potential endogenous adaptation to climate assumed in each area.

The statistical models of yield response in this study are specified as follows:

$$\mathrm{Y_i} = \alpha_1 + \alpha_2\left(\mathrm{T_{ji}}\right) + \alpha_3\left(\mathrm{T_{Yi}}\right) + \alpha_4\left(\mathrm{PP_{ji}}\right) + \alpha_5\left(\mathrm{PP_{Yi}}\right) + \mathrm{u_i} \tag{1}$$

where the subscript i refers to panel data observations, j refers to the month, and $_Y$ refers to the annual values. Y_i is the crop yield (kg ha^{-1}); T_{ji} is the temperature of the months (j) of the growing period (that varies due to location and crop; this is represented in the final specification of the model described in the results section) and T_{Yi} refers to the annual average; PP_{ji} is total water amount (precipitation plus irrigation) of the months (j) of the growing period received by the crop (mm) and PP_{Yi} refers to the annual average; α_1 to α_5 are parameters and u is the random term.

Our methodology expands process-based crop model results over large areas and therefore overcomes the limitation of data requirements for process based crop models; includes conditions that are outside the range of historical observations of crop yield data; and includes simulation of optimal management and therefore estimates agricultural responses to changes in regional climate. Because of the nature of our assumptions, we consider that the results represent an agricultural policy scenario that does not impose major additional environmental restrictions beyond the ones currently implemented, nor include pollution taxes (for example for nitrogen emissions to mitigate climate change).

2.5 Estimation of changes in economic variables

The potential economic impact of climate change derived from changes in agricultural productivity can be estimated with various methodologies (e.g. Darwin 2004; Kaiser et al. 1993; Reilly et al. 2003; Parry et al. 2004). Here we use a Computable General Equilibrium (CGE) model to simulate the macroeconomic effects in terms of gross domestic product (GDP) changes. The GCE models represent the functioning of the overall economy following a market-based approach. Prices play a key role as they are the main mechanism through which the economy adjusts to an external shock such as climate change. Supply and demand in all markets are equalised with the price changes, attaining what is called a general equilibrium in the economy. At the same time, the budget constraints of the economic agents (e.g. income for households) are met in equilibrium. The global CGE models consider international trade flows between countries.

The general equilibrium approach has been useful for understanding the economic consequences of climate change in agriculture (Hertel 1997; Stern et al. 2006). Changes in crop productivity as a consequence of climate change have an effect on the whole economy through a series of mechanisms. Firstly, the reduction of land productivity in the agriculture sector implies that less output can be produced with the same inputs (e.g. labour force). This would lead to a price increase in agriculture goods, provoking higher costs in the sector, affecting then the inputs markets. This reallocation of resources will then affect the rest of the sectors in the economy, for instance because of the higher wages. Moreover, the changes in agriculture and input prices will affect households decisions on consumption.

For the CGE simulation we use the global GTAP general equilibrium model system (Hertel 1997; Brockmeier 2000) calibrated to the year 2001 (GTAP 6 database), i.e. with a global data base that represents the world economy for 2001. GTAP is a multi-region open economy model. Our simulations are based on the aggregation of the GTAP model to 7 regions, 4 sectors, and 4 factors (Table 2). Note that it was necessary to convert the agroclimatic zones to the country level for the economic analysis with the GTAP model. The nine regions of the physical impact assessment (appearing in Tables 3, 4 and Fig. 3) have been aggregated into seven (in Table 2, Figs. 6 and 7): the Continental North and Continental South regions have been aggregated into Continental, and the Atlantic South zone has been integrated in the Mediterranean North and South, since this area just includes the north part of France and Portugal, that were included as a country in the Mediterranean region.

The future baseline without climate change is defined by pseudo-calibrating the model in the future (Bosello and Zang 2005). For this purpose, we used long-term projections of population increase (A2 and B2, depending on the considered scenario) and technological change. Modelling technological change can be challenging (Grubb et al. 2002). CGE models such as GREEN, GEM-E3 and G-cubed consider a constant improvement of energy efficiency, typically in a range of 0.5–2.5% a year (Grubb et al. 2002). The DICE model (Nordhaus 1993) assumes an exponential slowdown in productivity growth. In our simulations, we consider the DICE approach assumption for technological change

Table 2 Summary of the regional aggregation, sectors and factors considered for the GE simulation

Regional aggregation	Countries
Boreal	Finland, Sweden
Atlantic North	Ireland, United Kingdom
Atlantic Central	Belgium, Denmark, Germany, Luxembourg, The Netherlands
Alpine	Austria
Continental	Czech Republic, Estonia, Latvia, Lithuania, Poland, Slovakia, Bulgaria, Hungary, Romania, Slovenia
Mediterranean North	France, Portugal
Mediterranean South	Cyprus, Greece, Italy, Malta, Spain
Sector	**Components**
Crops	Paddy rice, wheat, cereal grains, processed rise, vegetables, fruits and nuts, oil seeds, sugar cane and sugar beet, plant based fibres, crop mix, vegetable oils and facts and sugar
Other agrarian goods	Wool, silk-worm cocoons, meat: cattle, sheep, goats and horse, meat products, food products, beverages and tobacco
Manufactures	Manufacture GTAP sectors
Services	Services GTAP sectors
Factors	**Components**
Factors	Land, labour (including unskilled and skilled labour), capital and natural resources (energy)

Table 3 Estimated coefficients of the statistical functions of yield response (Eq. 1)

	Boreal	Continental North	Continental South	Atlantic North	Atlantic Central	Atlantic South	Alpine	Mediterranean North	Mediterranean South
PP_4						0.0173		0.0157	0.0013
						(0.0015)		(0.0091)	(0.0005)
PP_5			0.0153					0.0056	
			(0.0115)					(0.0339)	
PP_6			0.0172	0.0153		0.0422			
			(0.0200)	(0.0013)		(0.0401)			
PP_7					0.1067				
					(0.0375)				
PP_8		0.0041		0.0102					
		(0.0257)		(0.0014)					
PP_9	0.0182								
	(0.0279)								
PP_Y	0.0055	0.0015	0.0102	0.0136	0.0298		0.0077		0.0112
	(0.0032)	(0.0265)	(0.0138)	(0.0104)	(0.0264)		(0.0001)		(0.0000)
T_4			0.1831						
			(0.0000)						
T_5		0.4759	0.0050			−0.0059		−0.2298	
		(0.0018)	(0.0000)			(0.0000)		(0.0003)	
T_6	0.0429	0.0050	−0.0571		0.1107		0.0193		
	(0.0017)	(0.0113)	(0.0045)		(0.0069)		(0.0462)		
T_7		−0.2731		−0.0056			0.0564	−0.0127	−0.0313
		(0.0038)		(0.0000)			(0.0357)	(0.0008)	(0.0004)
T_8	0.2010	−0.1571							
	(0.0001)	(0.0009)							
T_Y	0.0769	0.1572		0.2752	0.5105	−0.2014	0.3401		
	(0.0001)	(0.0009)		(0.0384)	(0.0173)	(0.0000)	(0.0081)		
R2	0.62	0.71	0.83	0.72	0.6	0.69	0.67	0.89	0.78

Standard deviations in parenthesis. PP_4 to PP_9 refer to crop water (sum of precipitation and irrigation) in months 4 to 9; PP_y refers to the annual average crop water; T_4 to T_8 refer to temperature in months 4 to 8; T_y refers to the annual average temperature

modelling, with an improvement of 1% per year in 2001 and the same constant decline per decade as in DICE.

For the economic valuation of impacts on the European economy, we have interpreted the physical impacts on European crop production as a land productivity shock. As the rest of the world would also experiences a productivity change, we have included it as calculated in Parry et al. (2004) for the HadCM3 A2 and B2 average scenarios in the 2071–2100 period (leading to a reduction of 0.3 and 1.5% in world average crop yields, respectively).

2.6 Limitations and sources of uncertainty

The main limitations of the analysis derive from the imperfect data (e.g. limited climate stations -see Peterson 2006- and observations for model validation - see Jones et al. 2003-), limitation of the models to represent complex reality (e.g. climate models, crop models and economic models are a simplification of the climate, agricultural, and social systems), and

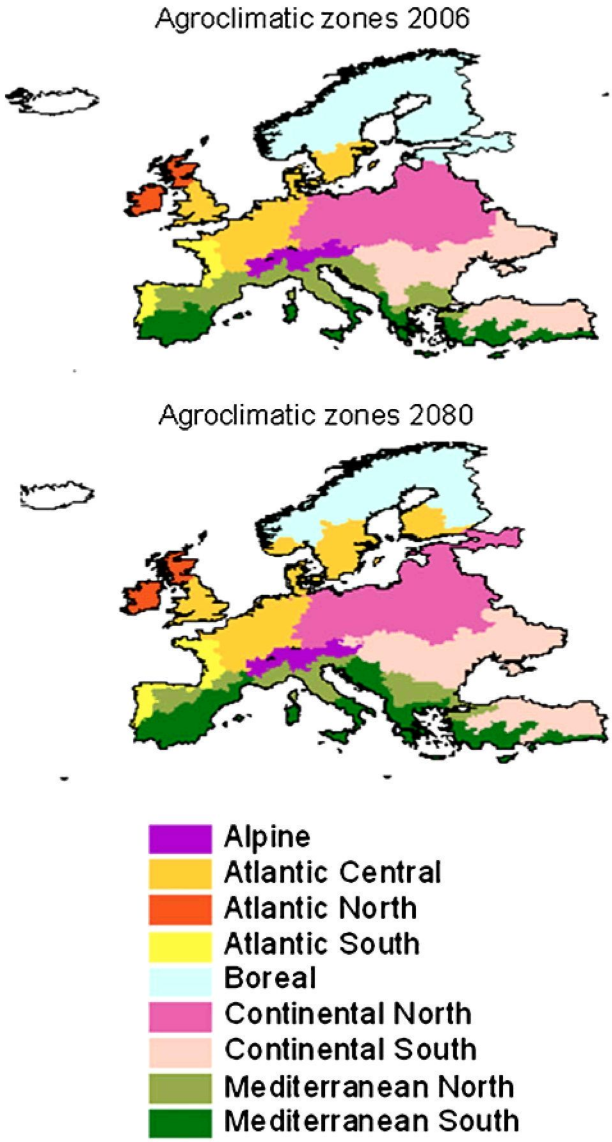
Table 4 Average regional changes in crop yield and coefficient of variation under the four scenarios for the period 2071–2100 compared to baseline

Region	HadCM3/HIRHAM A2 period 2071–2100		HadCM3/HIRHAM B2 period 2071–2100		ECHAM4/RCA3 A2 period 2071–2100		ECHAM4/RCA3 B2 period 2071–2100	
	Yield Change(%)	SD(%)	Yield Change(%)	SD(%)	Yield Change(%)	SD(%)	Yield Change(%)	SD(%)
Boreal	41	38	34	32	54	22	47	15
Atlantic North	−5	6	3	6	22	17	16	10
Atlantic Central	5	24	6	27	19	38	17	23
Atlantic South	−10	5	−7	3	−26	10	−12	9
Alpine	21	14	23	17	20	24	20	20
Continental North	1	2	4	2	−8	7	1	4
Continental South	26	17	11	19	33	30	24	6
Mediterranean North	−8	4	0	3	−22	8	−11	7
Mediterranean South	−12	41	1	43	−27	41	5	46

the assumptions about the future (e.g. evolution of technology and biotechnology). These limitations are the cause of uncertain results (defining uncertainty as the lack of exact knowledge and therefore to any analytical study, Hardaker et al. 2004; Vose 2000). The uncertainty of the crop models used is derived from the limitations if the model equations to represent agro-ecosystems dynamics and the data used to validate the imperfect models. The strength our model results is derived from the recognition that approach and models used here to develop statistical models of yield response is widely used (Lobell and Burke 2010; Parry et al. 2004; Iglesias et al. 2000) and that the data to validate the models is consistent with the climate data used to define the baseline of the study (same time period). Crop varieties evolve continuously and have advanced enormously in relation to crop resistance to pests and diseases (e.g. GM crops); nevertheless the main features of crops that determine response to temperature variations (phenology) are quite stable. A main source of uncertainty is derived from the climate scenarios, especially in the Mediterranean area where the important increase in climate variability is not included in the Prudence projections (Giorgi and Lionello 2008) and more developed in the Ensembles project Royer et al. 2009 – the data of the Ensembles project was not available at the resolution demanded for all sectors of the project that encloses this agricultural study). The assumptions used to derive climate change scenarios is a great challenge that is constantly being addressed (Moss et al. 2010; van Vuuren and O'Neill 2006). In summary, uncertainty can never be estimated in probabilistic terms since it reflects imperfect knowledge: here uncertainty is derived from the climate, the agronomic and the economic models.

In addition to the uncertainty, the results may present a probabilistic variation (risk, Hardaker et al. 2004; Vose 2000). Although this study does not focus on risk analysis, we introduce some risk aspects in the evaluation by selecting several scenarios, several geographical locations within each agro-climatic area, several crops and multiple years (30) for the simulations. The result is that we have several sets of values and each value is associated with a standard deviation.

Fig. 3 Agroclimatic areas under the baseline climate and under a climate scenario with a temperature increase of 3°C that represents average conditions of the scenarios considered in this study for the 2071–2100 period



3 Physical impacts

3.1 Agro-climatic regions

Agroclimatic regions present substantial changes as a result of climate change, as can be seen in Fig. 3. The results, derived from a simple agro-climatic approach, show a northward expansion of suitable agriculture areas, which is consistent with the results derived in more complex analyses that include many other variables such as the study of Rounsevell et al. (2006). Changes are especially large for farming systems in the northern areas of Europe and throughout the Mediterranean, with implications for the types of crops, crop management, and irrigation requirements in these regions. Changes in the Atlantic regions are smaller as result of the lower temperature changes expected in many coastal areas. The changes in the continental regions may have large implications for permanent and energy crops. These changes in agroclimatic regions have important implications for the evaluation of impacts on future crop productivity. Here, we use a statistical model of yield response in future agroclimatic regions - that is, the farmers in each location in the future are assumed to have knowledge of how and what to produce, as we shall see below.

3.2 Crop response to management

Farm level adaptation refers to changes in management decisions over time that will take place considering that farmers can learn from previous crop yield outcomes (Meza and Silva 2009). Even though agricultural responses to climate change tend to be crop and location specific, here we consider the possible modification of the following key factors, which imply no additional cost: planting date, nitrogen fertiliser, and water for irrigation. Examples of simulating changes in these management variables are shown in Fig. 4. For the exploration of the sensitivity to water and nitrogen the optimal plating date under current climate has been assumed. It coincides with the most widely used planting date in each area. The crop choice under climate change is implicit in the functional form applied in each agro-climatic region as described above.

The two socio-economic scenarios considered may have different implications for the coping capacity of farmers. This may indicate regional variations in coping capacity, improved at the local level in some areas but decreasing in areas of lower economic growth. For example, the B2 scenario may result in implications of the higher priority for the protection of natural ecosystems, or the A2 scenario may imply capacity to confront global problems such as trade; these differences are not considered in this study. Although these differences may result in different potential agricultural policy, this study only addresses endogenous adaptation. Therefore, in this study we consider that the A2 and B2 scenarios result in similar agricultural coping capacity for farmers in Europe.

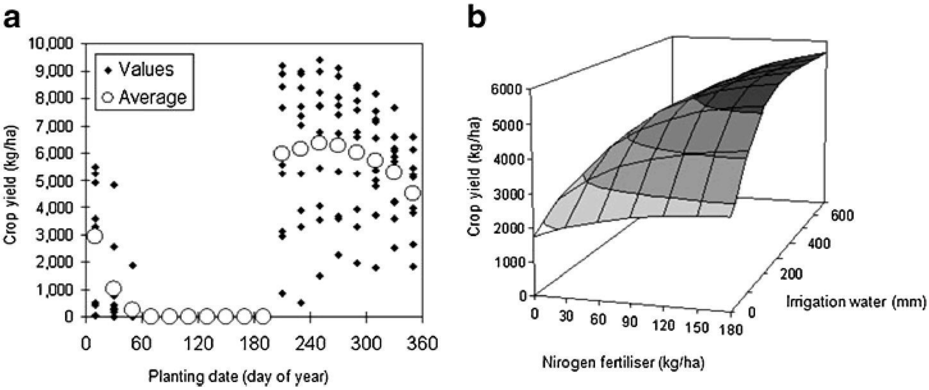


Fig. 4 (**a**) Simulated crop response to planting date (black dots represent annual values); (**b**) Nitrogen and water inputs in a dry site in Southern Europe (Almeria, Spain)

3.3 Statistical functions of yield response

Table 3 summarises the estimated coefficients and the standard deviations of the parameters of the statistical functions of yield response. These functions are then implemented across the 247 sites in Europe to derive spatial impacts of crop productivity under the climate change scenarios (results are shown in the following section).

3.4 Spatial productivity changes

There are considerable regional disparities in the possible impact of global change on crop productivity in Europe. Figure 5 shows modelled European crop yield changes for the four scenarios for the period 2071–2100. The crop productivity changes include the changes in crop distribution in the scenario due to modified crop suitability under the warmer climate and farmers adaptation as described above. Although each scenario projects different results, all scenarios are consistent in the spatial distribution of effects. Crop productivity increases in northern Europe are caused by a lengthened growing season, which decreases cold effects on growth and extends the frost-free period. Crop productivity decreases in southern Europe are caused by a shortening of the growing period, with subsequent negative effects on grain filling. The results in coastal areas are often difficult to interpret. In some cases, the higher uncertainty of the coastal results may be derived from the re-sampling of the downscaled scenarios to a common grid. Since the thermal inertia is much larger over sea than over land, gridpoints located close to the coast may include information from sea points in the process of re-sampling. The result is that temperature in climate change scenarios is dampened due to proximity to the sea. In all areas, it is very important to notice that the simulations considered no restrictions on water use for irrigation nor in the

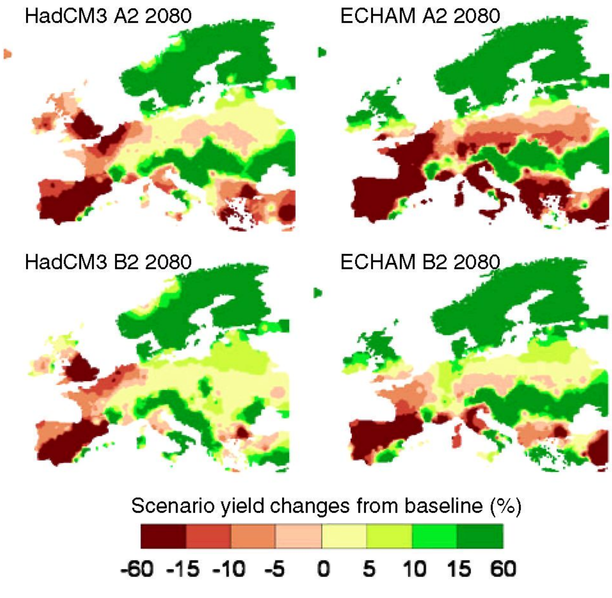


Fig. 5 Crop yield changes under the four scenarios for the period 2071–2100

application of nitrogen fertilizers. Considering potential impacts of climate change and the evolution of a society that places more emphasis on environmental well-being, future policies are likely to further control irrigation water and restrict the application of fertilizers. Therefore, the results may be considered optimistic from the production point and somewhat pessimistic from the environmental point of view. Table 4 summarises the average regional changes in crop yield and coefficient of variation under the four scenarios for the period 2071–2100 compared to baseline.

4 Economic estimates of the physical impacts

Projected changes in regional GDP, agriculture trade and labour price are presented in Fig. 6. The regional pattern of GDP changes is consistent with that of the physical impacts, which are all positive, except in the Mediterranean countries. The most important GDP gains seem to happen in the continental region, because of the relatively higher productivity gains. The effects on GDP are smaller than the productivity increases, since agriculture has a low share in the overall economy. However, in countries where agriculture is a key sector (i.e., agriculture has a high share of GDP) the effects are relatively higher.

Comparing the results of this study across scenarios with the same climate model but a different socio-economic driver, the effects on GDP vary more than the results for the same socio-economic scenario and different climate models. Therefore, the socio-economic signal (which includes population growth) has a larger influence than the climate signal on economic impacts in terms of GDP changes. This is relevant given that the physical impact studies do not usually capture the socioeconomic signal.

Figure 6 also shows that the changes in agriculture imports and exports are wider than the changes in GDP. Exports would increase and imports would decrease in most European regions, thanks to the lower crop prices induced by the productivity gains. An increase in crop productivity implies that with the same production factors (for instance labour and machinery) the output rises. The lower crop prices would lead to a competitiveness gain in world agriculture markets. Consequently, the region would export more, reducing its imports. In the Mediterranean regions the crop supply changes are negative, which result in higher prices.

The cost of labour moves in the same direction as land productivity (Fig. 6). When there are productivity gains, there is lower demand of the rest of production factors, decreasing their prices, as in the case of wages.

The A2 and B2 scenarios represent high and low CO_2 emissions pathways, respectively. Even if the scenarios do not consider explicit greenhouse gas emissions mitigation policies, one could interpret that the B2 scenario entails a certain reduction in emissions (mitigation action) compared to the A2 scenario. In this respect, the difference in the GDP impact between the B2 and A2 scenarios can be interpreted as the implicit benefit of mitigation policy. Figure 7 shows those differences in terms of changes in GDP in the 2080s in the European regions and the rest of the world. Each region has two bars: the black bar refers to the HadCM3 runs and the grey one to the ECHAM4 runs . The potential benefits from taking action to reduce greenhouse gas emissions seem to be significant in the Mediterranean regions.

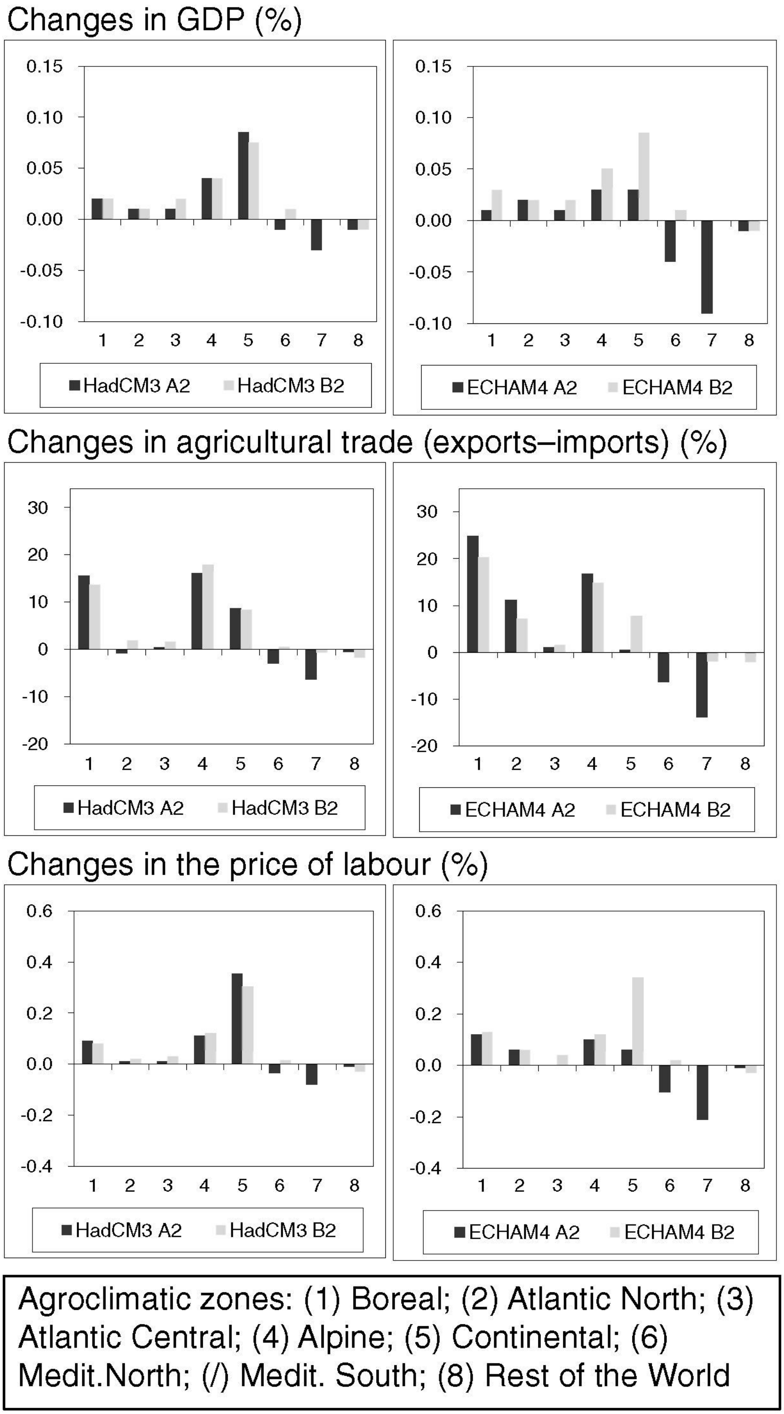
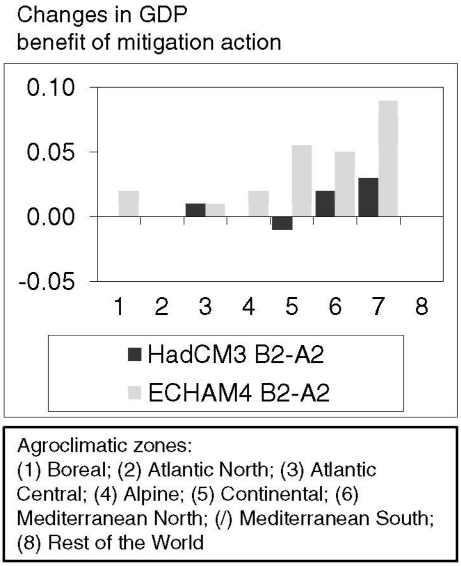


Fig. 6 Projected changes in GDP, agricultural trade and labour price (%)

Fig. 7 Potential benefits of mitigation action in terms of changes in GDP (%) in the 2080s



5 Conclusions

Three major points emerge from the results of this study. First, although each scenario projects different results, all scenarios are consistent in the spatial distribution of effects. Crop productivity increases in northern Europe and decreases in southern Europe. Second, the results may be considered optimistic from the production point and somewhat pessimistic from the environmental point of view, due to assumptions on optimal management. Third, trade patterns emerge as key drivers of economic impacts since changes in exports and imports vary relatively more than the other components of GDP.

There is large uncertainty surrounding future emissions and the potential development of their underlying driving forces. This uncertainty increases as one moves from emission values to climate change, from climate change to possible impacts and finally from these driving forces to formulating adaptation and mitigation policies (Gupta et al. 2003). We select two emission scenarios (A2 and B2) and two global climate models (HadCM3 and ECHAM) downscaled across Europe, to characterise uncertainty. In all regions, uncertainties with respect to the magnitude of the expected changes result in uncertainties of the agricultural evaluations (Olesen et al. 2007). For example, in some regions projections of rainfall, a key variable for crop production may be positive or negative depending on the climate scenario used and variable for different seasons. In general, our assessment shows that the estimated yield changes vary more among different climate models, while the GDP projections show more discrepancy across socio-economic scenarios. Nevertheless, the time horizon is the main determinant of the physical and economic projections.

The socio-economic scenarios are key factors for understanding the potential adaptation capacity of agriculture to climate change. Uncertainty regarding future population (density, distribution, migration), gross domestic product and technology determine and limit the potential adaptation strategies. However, evaluating the constraints to policy implementation is difficult (Smith et al. 2007; Urwin and Jordan 2008). In our study, the demand for and the supply of water for irrigation is influenced only by changes in the hydrological regimes, resulting from changes in the climate variables. Policy driven adaptation priorities may be derived from the impacts reported in this study.

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